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1. INTRODUCTION

This is a brief final in-house technical report for JON 4600P312, Massively Interconnect DOSP (Digital Optical Signal Processor). This research was conducted in the AF Photonics Center, in collaboration with support researchers from the University of Alabama working under an Expert in Science & Engineering contract.

The purpose of the effort was to build and demonstrate a highly interconnected optical processing stage using a novel architecture which makes possible high throughput, exceedingly low power operation. Basic interconnect feasibility was shown but the effort ended without demonstrating a working processing subsystem due to technical problems.

The basic subsystem design consists of a hologram or HOE (holographic optical element) which is an array of sub holograms, each of which illuminate a spatial light modulator (SLM) which in turn is detected by a CCD array. In figure 1, each sub-HOE is an image of an array of bright and dark pixels of the same dimensions as the SLM.

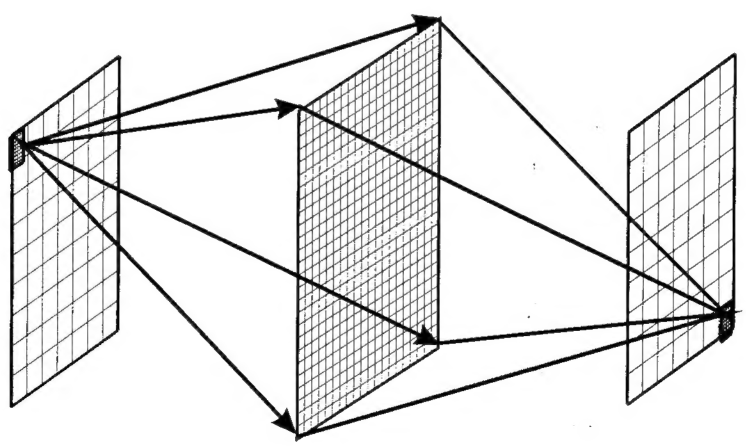

Figure 1. DOSP Optical Architecture

In fact, the intention was to form the sub-HOE by imaging different patterns produced by the SLM. Light from one sub-HOE (for example, the upper left sub-HOE in Figure 1) of the HOE array is imaged, pixel to pixel, onto the pixels of the SLM. These rays then in turn are focused and hence summed onto the corresponding (opposite lower right corner) pixel of the CCD array. Every sub-HOE is imaged independently and simultaneously through the entire SLM array onto the corresponding CCD elements in this fashion.

Logically, the binary 0 / 1, or dark / light values of the pixels stored in the sub-HOE are ANDed with the SLM pixel values, and then all products are summed or ORed onto the CCD pixel. In this way massive numbers of logic functions and interconnections are achieved[1]. If M^2 is the number of sub-HOEs, and N^2 is the dimension of the SLM and hence that of each sub-HOE in the HOE array, then $M^2 x N^2$ interconnects are made. If M=N, then N^4 interconnects are made. In the laboratory experiment planned, M=5 and N=256. That is, an array of 25 sub-HOEs each containing a 256x256 array of pixels was to be used with a 256x256 SLM and a 5x5 CCD array.

Note that in extreme low light level operation[2], a series of single photons can in principle illuminate the HOE onto the SLM and thence onto the CCD array. When sufficient light amplitude is accumulated at a particular CCD element, a detection is recorded. In this manner logic can be performed by the HOE - SLM - CCD system at energies far below that required by devices which involved intermediate light detection, or by electronics.

2. EXPERIMENTAL SETUP

In preparation for the experimental setup, the provided lab space needed to be made light tight, and remove as many of the ambient vibrations from the surrounding building as possible. Light in the room was restricted by taping down all of the ceiling tiles and placing cardboard blanks over the vents in the doors. Because the film is sensitive to green light (i.e. 514nm) we have removed or covered any indicator lights that are not red filtered, and have placed a red photographic safe light in the room for use during developing. Vibration in the room was reduced by use of air supported optical tables. Foam rubber was placed under the laser head of the five watt Spectra-Physics 2025 Argon-Ion laser and under the laser's water chiller to further eliminate these vibration sources. An optical lever was constructed using a small petri dish of water, and reflecting the laser off the surface of the water to a point approximately two meters away. Significant vibration could be seen as evident by the rippling beam image. Most of the vibration was due to the laser head so it was decided to isolate the laser on a separate optical table and use single-mode polarization preserving optical fiber to bring the light to the test set up table.

A simple Denazuk configuration was used (see figure 2) to establish the fact that

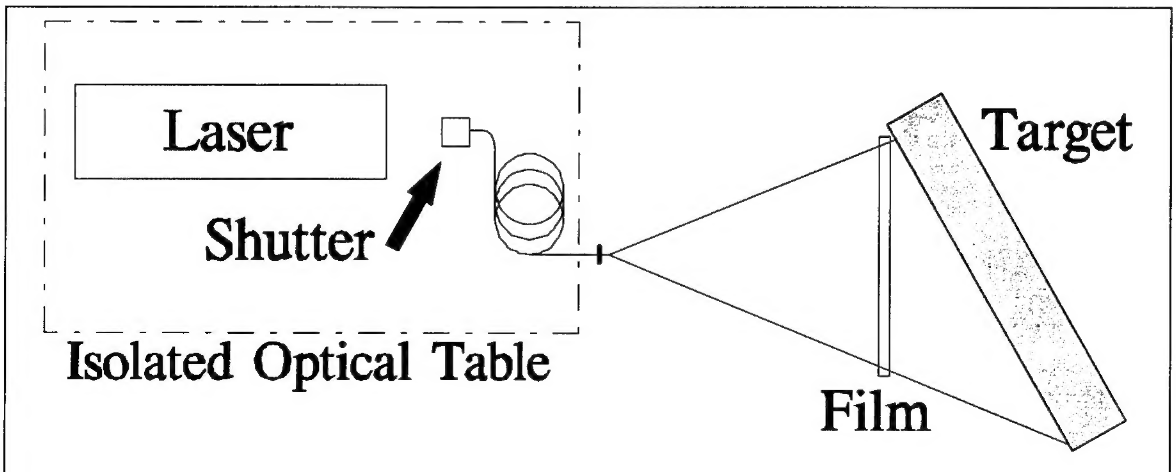

Figure 2 - Denazuk Hologram Configuration

holograms could actually be produced with the resources provided,

Using an oven heated etalon and prism, the wavelength was restricted to 514nm. A Newport shutter was placed in the beam's path before being injected into the fiber (this will eliminate the transient vibration of the shutter opening) and the other end of the fiber was used as a point source. The fiber illuminated a 4"x5" glass film plate (AGFA-GAVERT 8E56HD-6) with a target placed in close proximity. The beam would act as both the reference and object beams. As the light initially passed through the film it would set the reference pattern. The light would then strike the target and be reflected back onto the film, thus setting up the object-reference interference pattern. The target was an aluminum paint coated relief carving. By placing the target approximately at Brewster's angle, the finished display HOE could be viewed off-axis while reducing interfering reflections that would add noise to the image.

The test HOEs exposed only one quarter of the film plate at a time. The exposure energy density was varied with each exposure to provide a single plate comparison of 50, 100, 200, and 400 $\mu J/cm^2$. The required exposure times were calculated by measuring the incident optical power from the laser and then using equation 1.

$$\textit{Exposure Time} = \textit{Exposure Energy} / \textit{Incident Optical Power} \tag{1}$$

Using the measured power of 64.1μW the exposure times of table 1 were derived.

Exposure Time (seconds)	**Exposure Energy ($\mu J/cm^2$)**
0.78	50
1.56	100
3.12	200
6.24	400

Table 1 - Exposure times for display HOE

After exposure, the plate was developed using the CWC2 recipe in the Appendix. Equal parts of A and B were used, and the plate was left in the solution for two minutes. The exposures were thoroughly rinsed and then bleached using the Copper Sulfate bleach recipe in the appendix. This bleach allows the emulsion to be bleached, but it won't shrink the film -- an important consideration for this project as registration will be an issue later. After four minutes of bleaching, the plate was again rinsed and then placed in a redeveloper solution of 10 g Ascorbic Acid and enough water to make one liter. After a stop bath the plate was squeegeed dry, and then backed with black paint.

The clearest image was the 200 $\mu J/cm^2$ exposure. Four other full plates were then exposed. The first was developed as before with the exception that no redevelopment bath was used. The redeveloper changes the silver in the plate back to a state that closely resembles the original state, and so should reduce scattering. In comparing this image to the third and fourth plates (which were exact duplicates of the process above) a difference in the scattering of the images could be seen, but it was not a large change. In the later stages of the project, even a slight increase in noise due to scattering could cause problems, so the redevelopment stage will be used in processing.

The second plate was developed using a pyro-chrome bleach (see the Appendix for recipe). This was performed to note its effect. Because this process does not rehologenate the emulsion, the emulsion shrunk during development and the image shifted to shorter wavelengths. In fact, the image was a very deep blue color rather than green.

The final plates were developed as before for display purposes. One plate was retained by Rome laboratory while the other was sent to UAH.

Once the initial capability was shown, the final set-up could be established. This setup is

very similar to a Page Oriented Holographic Memory Printer (POHM). Figure 3 shows this layout.

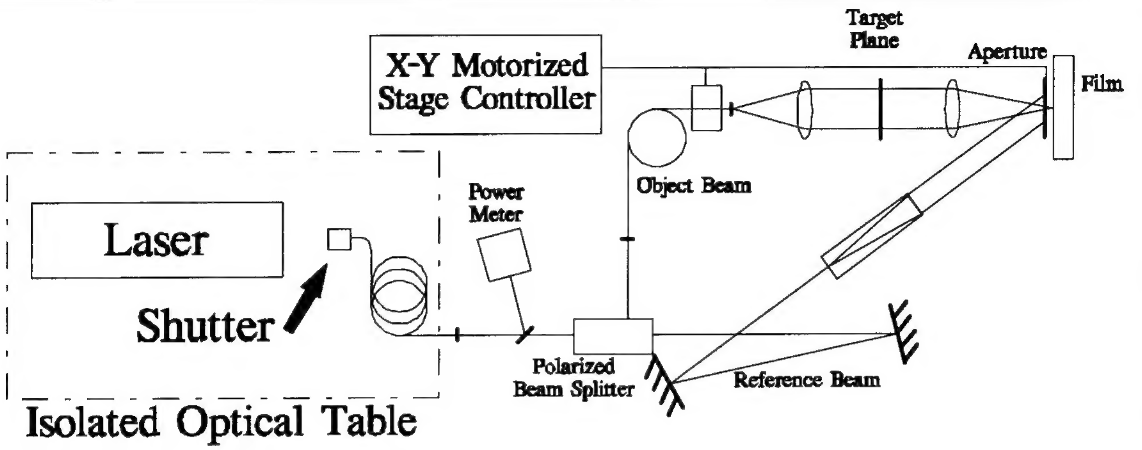

Figure 3 - Page Oriented Holographic Memory (POHM) Printer Layout

Again the laser and shutter were isolated on a separate optical table. This time, however, the shutter was controlled by a 386 class computer by being connected through an A/D board. With the shutter open, the light would exit the fiber and a power measurement made by a split from a glass slide. That measurement would be sent to the controlling computer for calculation of how long the shutter was to remain open. The beam would then pass through a polarized beam splitter to form the object and reference beams. The reference beam was reflected between two 2-inch mirrors that could be adjusted to allow matching the optical path lengths of both beams (a requirement for coherence). The reference beam was then expanded and collimated before it reached the exposure mask and film. The object beam is passed through a half wave plate for proper orientation before being inserted into another run of single-mode polarization preserving optical fiber. The end of this fiber is mounted on a motorized stage controlled via a GPIB interface to the computer. This fiber acts as a positionable point source. One focal length away from the fiber end is a 150mm lens. Another focal length away is the target image, then another 150 mm lens positioned an additional focal length from the target. This allows us to place the

information we want in the object beam. The exposure mask and film plate are located one more focal length from the last lens. Because the ratio between the reference beam and object beam is so critical, the object beam was defocused to a 4mm spot size (the size of our aperture) to prevent a single bright spot washing out the rest of the image. The exposure mask is mounted on another motorized stage, and moves in direct opposition to the fiber. This allows an array of images to be created using an array of point sources. During reconstruction, a detector was mounted in place of the fiber and measurements taken to show how the system works.

In examining the system, it was noted that there was a great deal of variance in the laser's optical power. A short test was made to monitor the stability over time. It was discovered that the laser power exiting the fiber varied from 70% to 135% of the mean. It was deemed that five measurements be made for every exposure and the average used to calculate the needed exposure time.

3. SOFTWARE

The computer software produced for this project was written in Pascal to allow compatibility with existing modules. It was used to integrate the many different functions of producing the needed exposures. There are four main divisions to the software: Shutter control, motion control, display, and SLM control. The shutter was controlled via an A/D interface card. The computer would open the shutter exposing the plate and a clock would be started to track the time the shutter had been open. A measurement taken from the glass slide reflection was used to calculate the beams incident power on the film from a preset ratio. The time for the exposure was then calculated and the clock was checked. The computer would continue checking the clock until the elapsed time was equal to or greater than the calculated time. The computer would then send a signal to close the shutter.

When the shutter was closed, the computer would use its GPIB interface to tell the motion controllers to move to the next position in the 5x5 matrix. As the controllers use stepper motors, control was provided by telling the stage which direction to go and how many steps to move. After the motion was complete a two minute timer was started to allow the transient vibrations to decay before the shutter was opened again.

The display presented the user with data about what position the POHM was addressing, the exposure energy, and the exposure time. Finally, the Semetex SLM control was provided by the computer. In the final experiment the target would be the SLM and the computer would change the images to those needed for the project. During reconstruction, the computer would control the masks on the SLM.

Details on image compression and other functions the completed processor could perform are detailed in References 3, 4.

4. TEST RESULTS

Tests of the system showed us that some vignetting was occurring in the object beam. Two plates were produced, each with a 5x5 array of spots (no target). The first used varying exposure energy densities to check the response of the film and was fixed for later density tests. The second was producing using a constant 200 $\mu J/cm^2$ energy density and then developed normally. A plot of the density measurements is shown in figure 4.

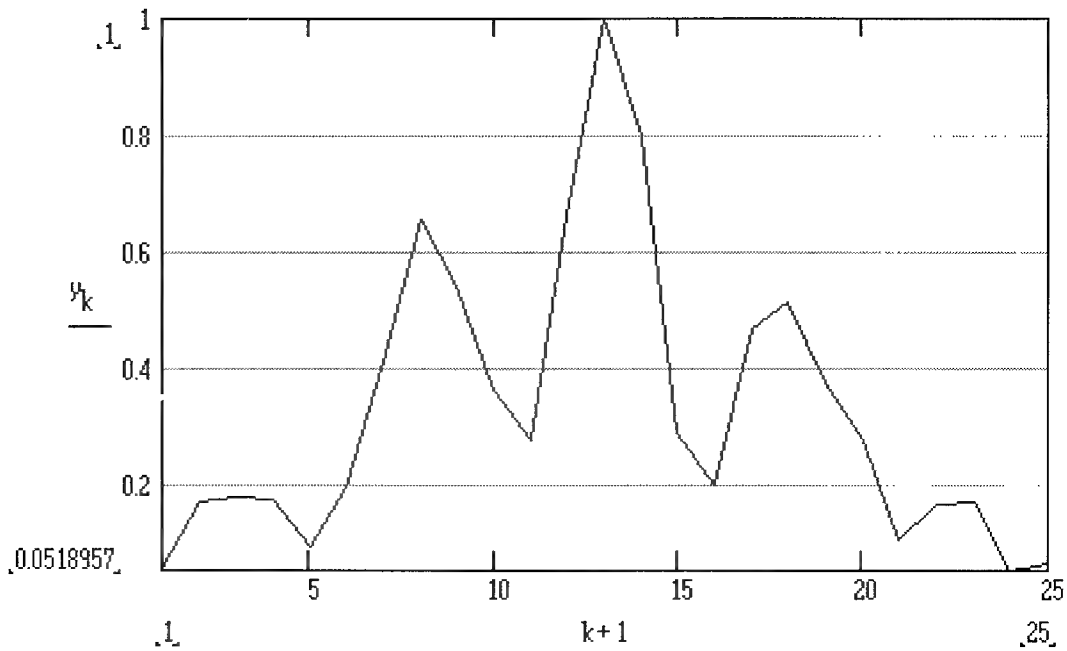

Figure 4 - Efficiency vs. Position of Exposure

As can be seen, all of the middle points are within 10% of the expected value (the error bars represent +/- 10%). Because of the T-E curve, the end points will be non-linear and should level out as in the figure. The efficiency measurements, however, revealed the vignetting problems.

As can be seen in the plot of figure 5, there is a spatial correlation of the efficiency with the distance from the center.

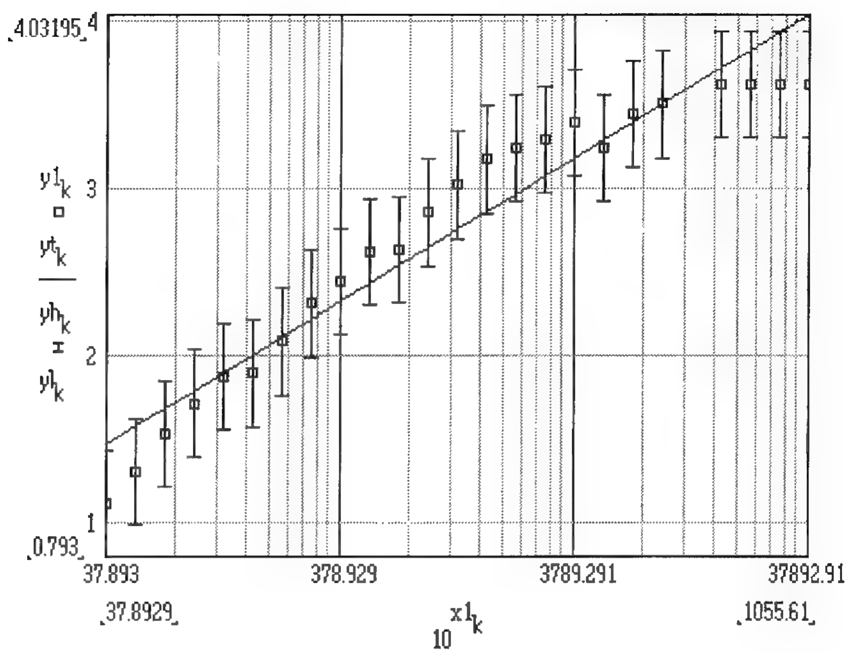

Figure 5 - Plot of Measured Density vs. Exposure Curve

Two items of interest should be noted in figure 5. The first is the envelope formed by the local maxima. Each of these maxima occurs at the center element of each row. As the rows range further from the central point, both the density and efficiency drop off. This is due to vignetting caused by the vertical motion of the stages. The second point is the local minima and maxima. The minima occur at the extremes of each row. This drop is due to vignetting caused by the horizontal motion of the stages.

A field lens was placed in the system between the fiber and the first 150mm lens. The motion of the stages that controlled the fiber point source were then adjusted so that the vignetting problem was eliminated.

Near the end of system development it was found that the SLM, especially procured for this experiment, had electronic problems. To complete the project in a timely fashion it was decided to substitute fixed masks for the SLM and demonstrate massive interconnection only. A number of fixed masks were fabricated and used to shoot the 5x5 array of 256^2 sub-HOEs, instead of using the SLM. The HOE and masks were then used in tandem to successfully demonstrate massive optical interconnection, concluding the effort.

In a future effort a working SLM and additional stages of logic could be used with photo multiplier tubes or micro channel plate CCD to demonstrate true high throughput, low light level digital optical computing, now that basic interconnect feasibility has been shown.

5. CONCLUSIONS

In this in-house effort considerable design, programming, and experimental work, documented above, was conducted which succeeded in demonstrating the feasibility of the basic massively parallel holographic architecture. A $5^2 \times 256^2$ optical interconnect was demonstrated, but due to the failure of the SLM, a working processor subsystem could not be completed. Low light level operation could potentially reach sub-kT levels in future research, and a complete general computing system could be demonstrated by adding additional stages of logic.

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7. APPENDIX

Holographic Development Recipes:

CWC2 Developing Solution

Part A

20g	Catechol
10g	Ascorbic Acid
10g	Sodium Sulfite
50g	Urea

Water to make one liter

Part B

60g	Sodium Carbonate

Water to make one liter

Copper Sulfate Bleach

35g	Copper Sulfate
10ml	Glacial Acetic Acid
110g	Potassium Bromide

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